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RE-EVALUATION OF SEISMIC TORSIONAL PROVISIONS

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SUMMARY

Traditionally, seismic torsional provisions have been evaluated based on the assumption that the strength of the lateral load resisting elements can be adjusted without changing their stiffness. There is an important class of elements that a change of their lateral strength implies a corresponding change of stiffness, as exemplified by reinforced concrete flexural walls. This would imply that when torsional provisions are applied to adjust the strengths of these elements, the stiffness distribution, and also the eccentricity of the system, will change. This paper re-evaluates the consequences of applying the torsional provisions of the Uniform Building Code (UBC, 1997) and also the Eurocode (Eurocode 8, 1994) to single mass eccentric systems supported by elements having such characteristics. In conjunction with the results based on the traditional assumption, the effectiveness of the two provisions to mitigate torsional effects is discussed from a broader perspective. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: torsion; building codes; earthquake engineering; rotations; structures; dynamics

INTRODUCTION

Excessive torsional response is believed to be the main cause of the poor seismic performance of many asymmetrical buildings. Torsional response always leads to an increase of displacements on the flexible side, and may cause a decrease of displacements on the stiff side of the eccentric structure. To mitigate the effect of torsion, most seismic codes provide guidelines commonly referred to as torsional provisions. Typically, the torsional provisions require an increase of strength for elements located on the flexible side, and may allow some decrease in strength for elements on the stiff side of the structure. A number of studies have been carried out to evaluate the efficiency of torsional provisions in different seismic codes,[1−5] among others. In all these studies, the evaluation is judged on the ability of the torsional provisions to minimize or eliminate the effect of torsion on the additional ductility and the displacement demands at the perimeter of the eccentric structure. One general consensus of the studies is that design incorporating torsional provisions will lead to a reduction of ductility demands on elements located at the flexible side of the structures. The ductility demands on elements on the stiff side may or may be not be reduced, depending on a number of factors. One primary factor is the allowable reduction of strength for these stiff edge elements. Codes that allow no reduction such as the Uniform

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Building Code[6] usually lead to ductility demands that are similar to or less than those of a symmetric structure of comparable construction. For codes that have no restriction on the reduction of strength, such as the Eurocode,[7] the ductility demands of the stiff side elements can be significantly increased. Another consensus is that the torsional provisions do not seem to have a great effect to reduce the additional edge displacements of the structure.[8,9]

The observations from all the studies are the by-product of one common assumption used, namely, that modification of element strength can be achieved without changing its elastic stiffness. Therefore, application of code provisions will not change the stiffness distribution or the stiffness eccentricity of the system. Approximating the behaviour of the lateral load resisting elements as being elasto-plastic, the force–displacement relations of two elements having similar geometric dimensions but having different yield strengths can be schematically illustrated in Figure 1(a). For ease of reference, elements having such characteristics will be referred to as "Stiffness Constant-type elements", or K-type elements for short. In a K-type element, an increase of strength has the effect of increasing its yield displacement. Therefore, a strength increase in a K-type element would in general reduce the ductility demand on that element. Since all code provisions require additional strength applied to the elements at the flexible side, the increase of seismic displacements caused by torsion is presumed to be compensated by the increase of the yield displacements of these elements. This compensation often results in the ductility demands on the flexible side elements being even less than a similar but symmetrical structure. However, the seismic displacements on the stiff side are not reduced if the structure is torsionally flexible.[9] If large reductions of strengths (and consequently the yield displacements) of the stiff side elements are allowed, excessive increase of ductility demands on the stiff side elements in torsionally flexible structures can be expected.

Recently, it has been pointed out that representing the characteristics of all lateral load resisting elements as K-type elements is one of the fallacies between design and reality in earthquake engineering.[10] Extensive analyses of reinforced concrete bridge columns show that the yield strength and the stiffness of members are related.[11] Approximating the lateral behaviour of reinforced concrete flexural walls as elasto-plastic, it is shown that the yield strength can be considered to be proportional to the wall stiffness with the constant of proportionality being the yield displacement of the wall.[12] The force–displacement relations of two flexural walls of similar geometric dimensions but having different yield strengths can be represented by Figure 1(b). Elements with such characteristics will be referred to as "Yield Displacement Constant type elements", or D-type elements. When the torsional provisions are applied to a structure consisting of D-type elements, the required increase of strength in the flexible side elements will also increase the stiffness of these elements. This would shift the Centre of Rigidity (CR), decrease the eccentricity and reduce the torsional response of the structure. It is this reduction in torsion induced displacements and not the increase of yield displacements that modifies the ductility demands of the flexible side elements. Allowing strength reduction on the D-type elements at the stiff side also reduces the eccentricity of the structure, but there is no reduction of the yield displacements. Therefore, the excessive additional ductility demands on the stiff side elements may not be as critical as perceived from past studies.

Since all previous evaluations of torsional provisions are based on the K-type systems, the consensus would not apply to D-type element systems. The purpose of this study is to carry out a re-evaluation of the torsional provisions applied to structures supported by D-type elements, and compare the results with those when the provisions are applied to K-type systems. Two code provisions will be used in this study: the provision from the UBC which does not allow strength

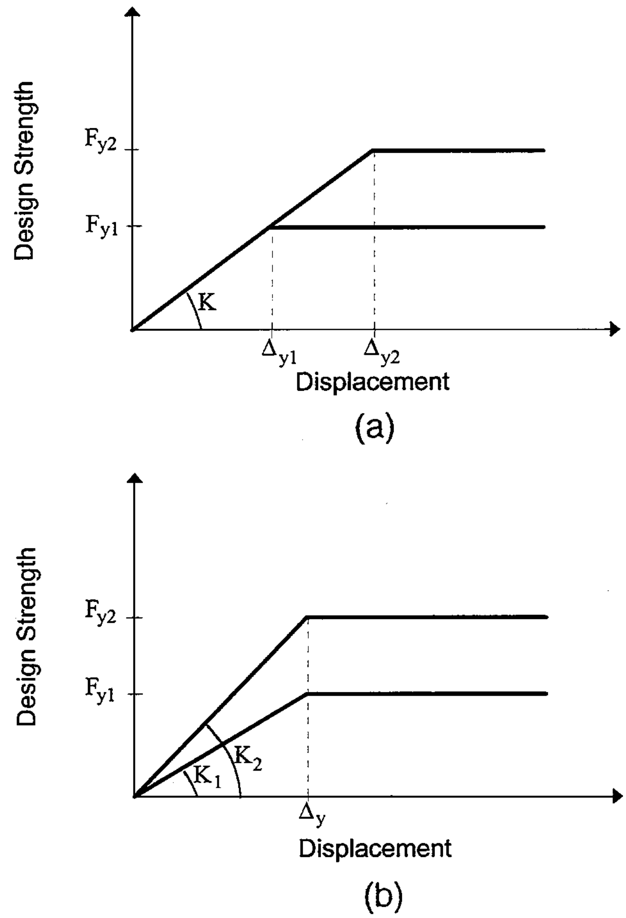

Figure 1. Characteristics of lateral load resisting elements. (a) *K*-type element, (b) *D*-type element

reduction for the elements located at the stiff side, and the provision from the Eurocode which allows full reduction of element strength as a result of negative shears from torsion.

A TYPICAL *D*-TYPE ELEMENT

Consider a series of four geometrically identical reinforced concrete flexural walls. These walls have overall dimensions of $h_w = 15$ m, $l_w = 3$ m, and $b_w = 0{\cdot}4$ m, with the reinforcement ratios ranging from 1·2 to 3·7 per cent. The walls with higher reinforcement ratios have more reinforcement concentrated near the edges as shown in Figure 2. The moment–curvature relations of these walls are computed using the computer program RESPONSE which performs the analysis of the capacity of a concrete section using the concepts of strain compatibility.[12] Figure 3(a) shows the moment–curvature relation of the walls. While the more heavily reinforced walls have

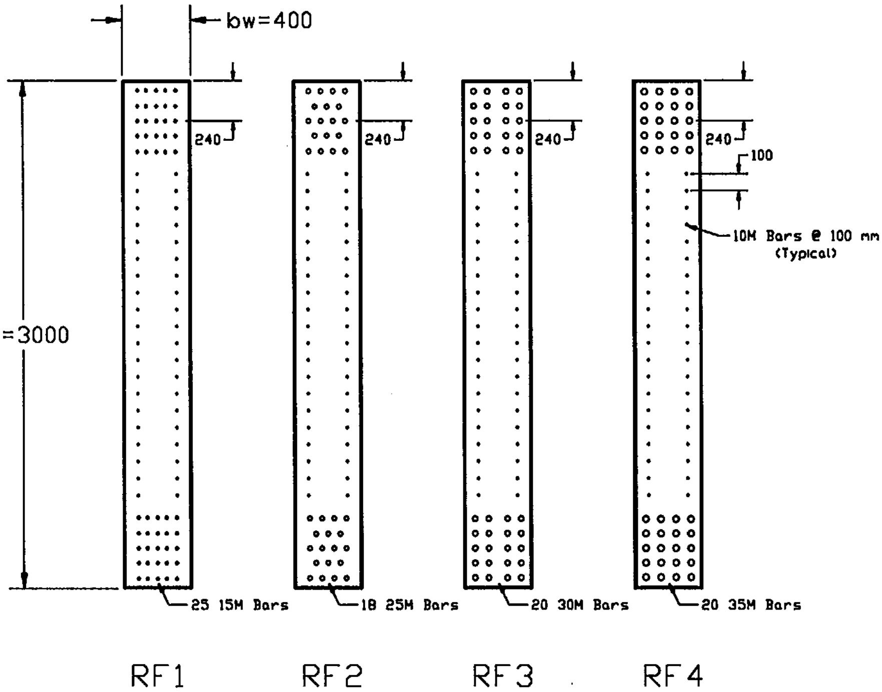

Figure 2. Reinforcement patterns for 3 m long walls. (All dimensions in mm)

a higher strength, the yield curvatures of the walls are essentially the same and can be determined using the expression[13]

$$\phi_y = \frac{1{\cdot}56 f_y}{E_s l_w} \tag{1}$$

where f_y and E_s are the yield strength and modulus of elasticity of the steel reinforcement, respectively. As a first approximation, the moment–curvature curves can be considered to be elasto-plastic as shown by dashed lines in the same figure. For walls of prismatic section, the elasto-plastic moment–curvature relationship can be transformed to an elasto-plastic force–displacement relationship using a yield displacement δ_y given by

$$\delta_y = \phi_y \left(\frac{h_w^2}{3} \right) \tag{2}$$

as presented in Figure 3(b). A comparison of this figure to Figure 1 shows that reinforced concrete flexural walls can best be characterized as *D*-type elements, instead of *K*-type elements as assumed traditionally. Similar observations have been pointed out by other researchers.[14]

STRUCTURAL MODEL

To examine the seismic response of eccentric systems supported by *K*-type elements, or *D*-type elements, a single-mass six-element model is adopted.[15] The model consists of a rigid square slab

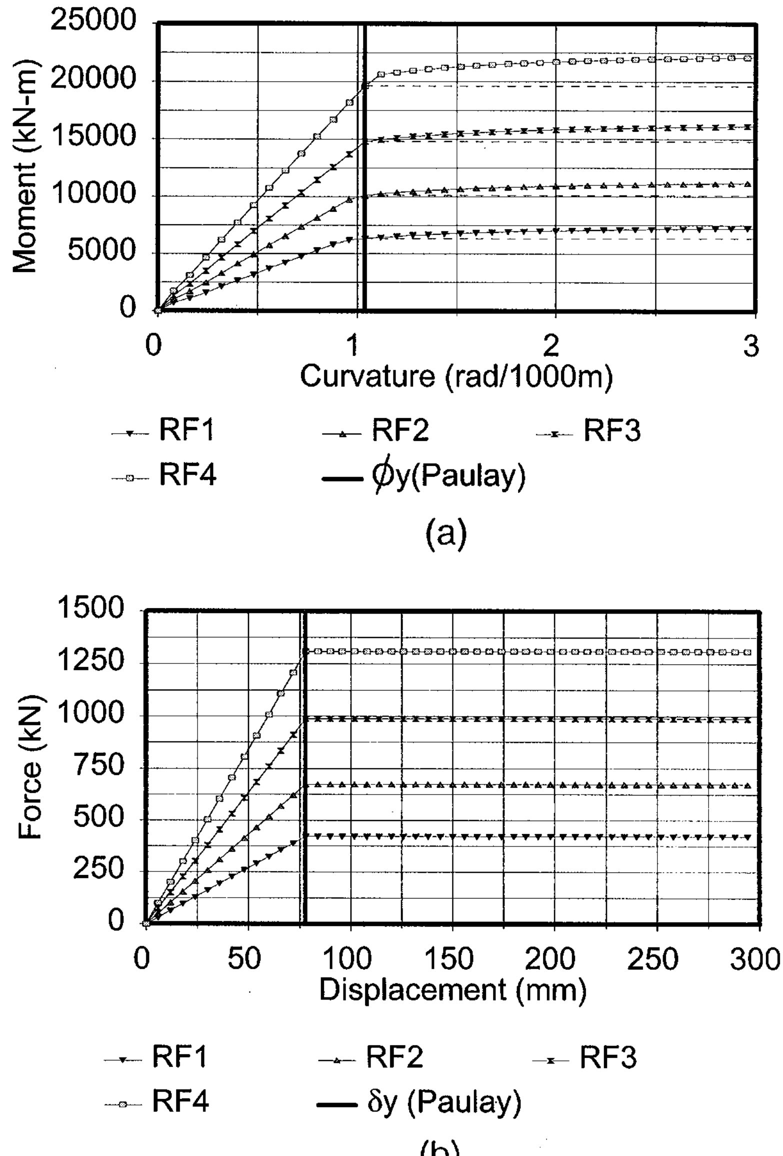

Figure 3. Deformation characteristics of a 3 m flexural wall with concentrated end reinforcement. (a) Moment–curvature, (b) force–displacement

of mass M and dimensions $b \times b$, supported by six massless lateral load resisting elements as shown in Figure 4. Elements 1, 2, and 3 resist lateral forces in the Y-direction and elements 4, 5, and 6 resist forces in the X-direction. Each element provides stiffness and strength in its own plane, and the out-of plane stiffness and strength are negligible. All elements have bilinear

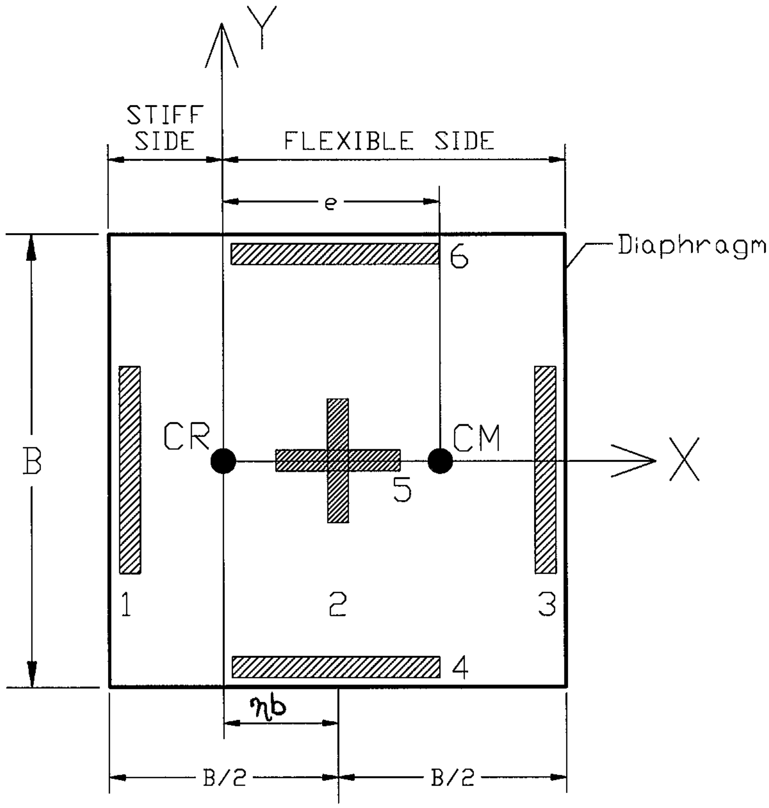

Figure 4. Torsionally unbalanced single-mass system

hysteretic force–displacement characteristics, with the secondary stiffness equal to 3% of the initial stiffness. The location of the Y-direction elements are fixed where element 2 is at the geometric centre and elements 1 and 3 are at the opposite edges of the slab. The X-direction element 5 is at the centre and elements 4 and 6 are at equal distances from element 5.

The stiffness of the elements are determined based on the following criteria. The total stiffness in the X- and Y-directions are identical and equal to K. Elements 4 and 6 are identical so that the X-axis is an axis of symmetry. The stiffness of the Y-direction elements are such that the centre of rigidity (CR) is located at ηb ($\eta \geqslant 0$) to the left of the geometric centre of the slab. The CR is taken as the origin of the X–Y co-ordinate system. Finally, the X-direction elements and Y-direction elements contribute equally to the total torsional stiffness K_θ of the system. The torsional stiffness of the system is represented by the normalized radius of gyration of stiffness ρ_k, defined by

$$\rho_k = \frac{1}{b}\sqrt{\frac{K_\theta}{K}} \tag{3}$$

The maximum and minimum values of ρ_k are dictated by the requirement that none of the six elements can have negative stiffness. Studies have shown that systems with ρ_k less than 0·35 are torsionally too flexible and that static loading incorporating torsional provisions does not

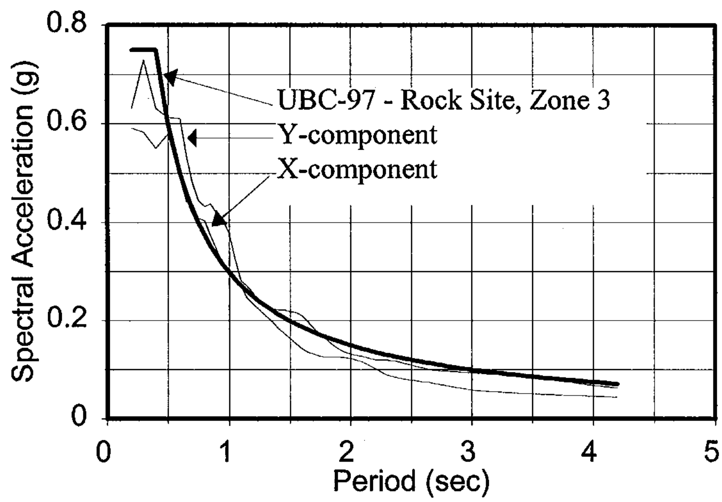

Figure 5. Mean 5 per cent damped input spectra and the elastic design spectra

represent well the actual seismic loading on the system.[15] Therefore, only systems with ρ_k larger that 0·35 are considered.

The nominal design lateral strengths of the torsionally unbalanced (TU) system in both directions follows the UBC-97[6] design spectrum for a rock site in Zone 3. A strength reduction factor $R = 5$ is used in each direction so that all elements would be excited well into the inelastic range when the system is exposed to the design-level ground motions. The excitation for the structural model consists of 10 pairs of earthquake records normalised to a peak ground acceleration of 0·3 g.[4] The mean 5% damped spectra of both the X and Y components of these records together with the UBC design spectrum are shown in Figure 5.

The horizontal distribution of the design strength to the elements according to the UBC torsional provision has been given.[15] Also, the implication of distributing strength according to the provisions of the Eurocode can be found.[17] Therefore, they will not be repeated here.

The inelastic responses of the TU system subjected to bi-directional input base motions are computed using the Newmark-beta method. A 5 per cent viscous damping in the first two modes of vibration is incorporated into the dynamic model. Computation is carried out for systems having an uncoupled lateral period equal to 1 s.

INELASTIC RESPONSES

The response parameters of interest are the maximum displacements and ductilities of element 1 at the stiff edge and element 3 at the flexible edge of the TU system. To show the torsional effect, these responses are normalized by their counterparts obtained from a reference model to form displacement and ductility ratios. The torsionally balanced (TB) model used by Tso and Wong[4] is adopted here as the reference model. It has an identical stiffness distribution to its TU counterpart, but it is torsionally balanced because it has a mass distribution such that its CM coincides with the CR. The total strength of the reference system in each direction is distributed to the

elements in proportion to their stiffness and without incorporating accidental eccentricities. As a result, there is no torsional response from the reference model, both in the elastic and inelastic ranges of response. Additional displacement or ductility demands resulting from the torsional response of the TU system can be detected readily when the displacement or ductility ratios become greater than unity. To smooth out the variation due to different earthquake records, only the means of the displacement and ductility ratios are presented. Two eccentric systems are studied. They are the stiffness eccentric system and the mass eccentric system.

Stiffness eccentric systems

In the stiffness eccentric systems, CR is located at $0{\cdot}2b$ to the left of the geometric centre ($\eta = 0{\cdot}2$) while the mass of the slab is uniformly distributed so that its CM coincides with the geometric centre. Therefore, these systems have an eccentricity equal to $0{\cdot}2b$ caused by the uneven distribution of stiffness. The design strengths of these TU systems are distributed to the resisting elements in three ways. First, no torsional provisions are used. The responses of elements 1 and 3 from such a stiffness proportional (SP) model are denoted as SP-1 or SP-3, respectively. In both the second and third approaches for strength distribution, the torsional provisions are followed. In the second approach, the elements are considered as K-type elements where the stiffness of the element remains unchanged while the strength changes. Results of elements 1 and 3 in this case are denoted as K-1 and K-3. In the third approach, elements 1 and 3 are considered D-type elements and their responses are denoted as D-1 and D-3.

Systems using UBC torsional provision

The mean displacement ratios of both elements 1 and 3 are plotted as a function of the torsional stiffness parameter ρ_k as shown in Figure 6. The overall trend of the curves is that the displacement ratio decreases as the torsional stiffness of the system increases, as one would expect. Another observation is that the displacement ratios for element 3 at the flexible edge exceeds unity, indicating there will be additional displacement at this edge. Not using any torsional provision, the additional displacement is in the order of 35 to 55 per cent over the reference model. Some marginal improvement can be gained using the UBC provisions for the K-type elements. However, if the elements are of the D-type, the improvement is significant, with the displacement ratio range reduced to between $1{\cdot}1$ and $1{\cdot}2$. For practical purposes, an increase of edge inelastic displacement in the order of 10–20 per cent due to torsion can be considered acceptable. Therefore, application of the UBC provisions can be an effective way to control the flexible edge displacement of D-type systems such as eccentric wall structures.

The reason for such reduction can be seen by examining the change of eccentricity of the system when UBC provisions are applied to the K- and D-type elements. For systems containing K-type elements, any change of strength as required by UBC provisions does not change their stiffness and the system eccentricity remains at $0{\cdot}2b$, the same as systems designed not using any torsional provisions. However, the strength increase will increase the stiffness of element D-3. This increase in stiffness causes the CR of the system to shift toward the CM. As a result, the effective stiffness eccentricity of the system will be reduced, as shown in Figure 7. This would reduce the torsional response for the D-type element systems. Another benefit of the CR shift is the reduction of the distance between CR and element D-3. The amount of distance reduction from $0{\cdot}7b$ can be seen from Figure 8. It is this combination of reduction of eccentricity and lever arm which makes the

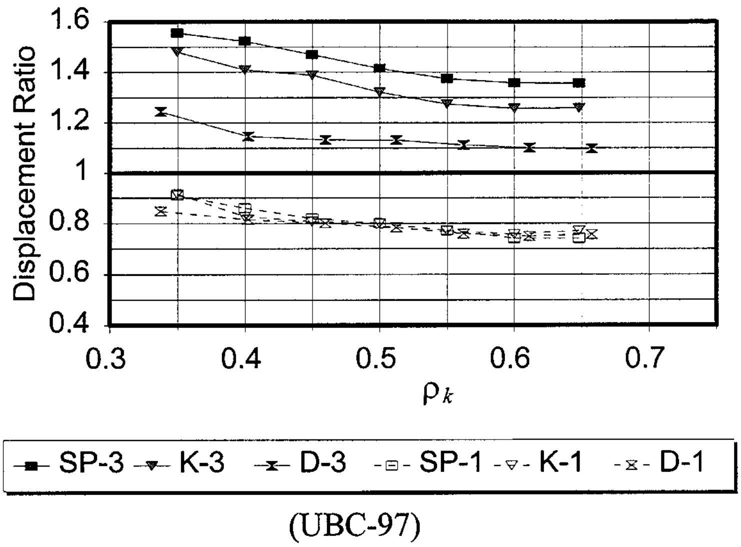

Figure 6. Mean displacement ratios of elements 1 and 3

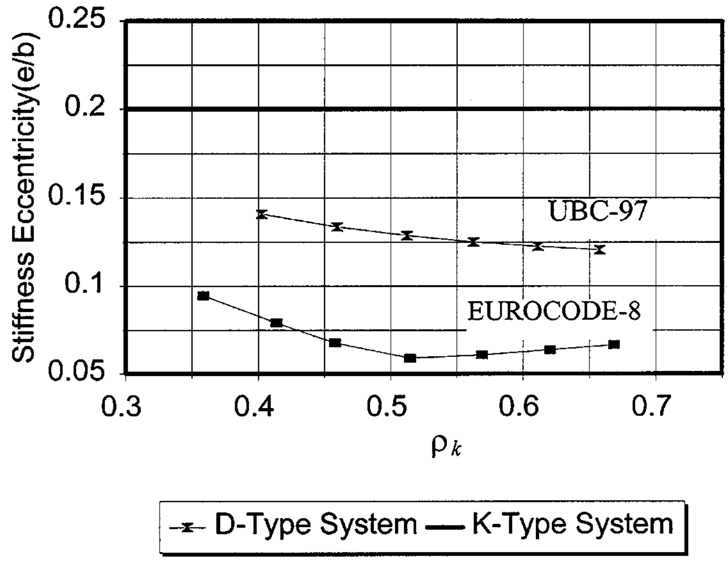

Figure 7. Effective stiffness eccentricity after application of torsional provisions

application of the torsional provision particularly effective in controlling the flexible edge displacement of *D*-type element eccentric systems.

The displacement ratios for element 1 as shown in Figure 6 are not sensitive to the way the design strength is distributed to the elements. All three approaches to strength distribution result

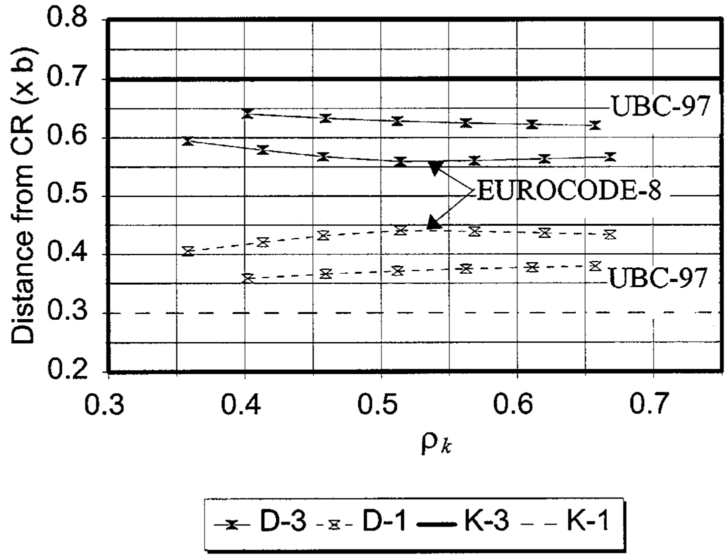

Figure 8. Effective distance from CR to elements 1 and 3 after application of torsional provisions

in similar displacement ratios. They are all less than unity, indicating that there is some reduction of displacements at the stiff edge of these eccentric system. The reason why application of UBC provision to *D*-type element structures does not lead to a lower displacement ratio than *K*-type element structures can be explained using the change of eccentricity and lever arm argument. While the eccentricity of the *D*-type element structures will be reduced due to the CR shift, this CR shift causes a lengthening of the distance between CR and element 1 from 0·30*b* to about 0·39*b* as shown in Figure 8. Therefore, the effect of the shifting of CR on the stiff edge displacement is self compensating, and this explains the indifference of the response results.

The mean ductility ratios for element 3 at the flexible edge are shown in Figure 9(a). Applying the UBC provision to *K*-type element structures, the ductility ratio of element *K*-3 is greatly reduced such that there will be no additional ductility demand for this element. However, there is about a 10–20 per cent increase of ductility demand on the *D*-3 element. In both cases, the ductility ratios are less than those if no torsional provision is used. The ductility ratio of *K*-type system increases while the ductility ratio of the *D*-type system decreases with the torsional stiffness of the system. This divergence can be explained by understanding how the ductility ratio reductions are achieved in each case. In the *K*-type element structure, application of UBC provision to element 3 increases its yield displacement. The more torsionally flexible the system, the larger will be the increase in design strength for element *K*-3, and correspondingly, the larger is the increase of its yield displacement. It is this increase in element 3 yield displacement which leads to a lowering of ductility ratios for the *K*-3 element, especially for torsionally flexible systems. The mechanics that lead to the reduction of ductility ratio for the *D*-3 element is different. The yield displacement of element *D*-3 has not changed. The reduction of the ductility ratio is a result of an overall reduction of torsional response of the system as discussed in the previous section. It is the reduction of seismic displacements which lead to the reduction of ductility demands on element *D*-3.

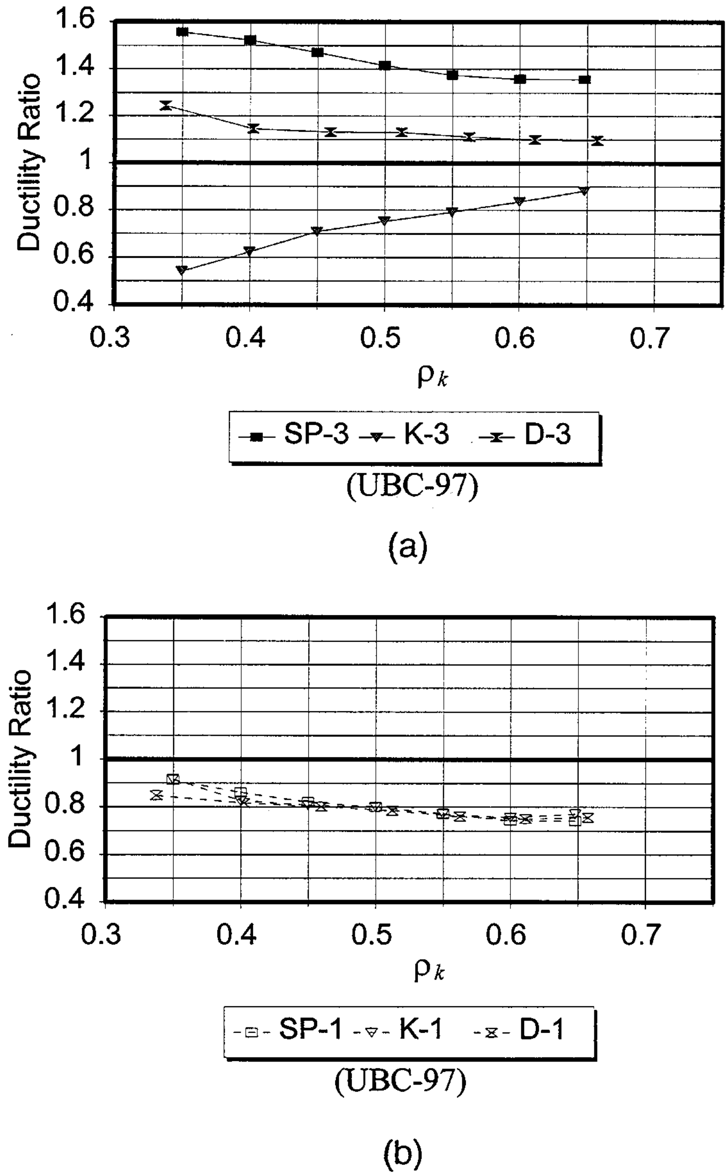

Figure 9. Mean ductility ratios: (a) element 3; (b) element 1

The mean ductility ratios for element 1 at the stiff edge are compared in Figure 9(b). All the curves are below unity, showing that torsion does not cause additional ductility demands for the element at the stiff edge. This is a consequence of the UBC torsional provision not allowing negative shear to be include in the design. The strength of element 1 remains unchanged irrespective of whether the torsional provision is applied or not.

Systems using eurocode torsional provision

The mean displacement ratios for systems using the Eurocode torsional provision are shown in Figure 10. The curves have the same general trend as those systems designed using the UBC provision. The major difference is that the Eurocode is more effective in reducing the additional displacements at the flexible edge of D-type element systems. There are essentially no additional displacements at the flexible edge. The reason is that the Eurocode not only requires increases in the strength of element 3, but also allows reduction of strength in element 1 at the stiff edge. This combined action drastically changes the stiffness distribution and shifts the CR significantly towards the CM of the system. The stiffness eccentricity of the system is reduced from $0{\cdot}2b$ to less than $0{\cdot}1b$, as shown in Figure 7. In addition, the distance from CR to the flexible edge is also correspondingly reduced as shown in Figure 8. This combination leads to the displacements at the flexible edge essentially the same as the reference system.

The ductility ratios for element 3 and element 1 are presented in Figure 11(a) and (b), respectively. Similar to using the UBC provision, the ductility ratios for K-type element at the flexible edge (element 3) are less than unity. Of more interest is the good control of the ductility for D-type elements at this edge. There is essentially no increase in ductility demand.

However, it should be of concern that the ductility ratio can be very large for the K-1 element in torsionally flexible systems. The reason is that for torsionally flexible systems, the negative torsional shear can be large. By allowing design to incorporate negative torsional shear, one will greatly reduce the strength of element 1. If element 1 is a K-type element, this implies that the yield displacement will be correspondingly reduced, which leads to a high ductility demand. This high ductility demand does not show up if element 1 is a D-type element since reduction in strength does not imply reduction in yield displacement for D-type elements.

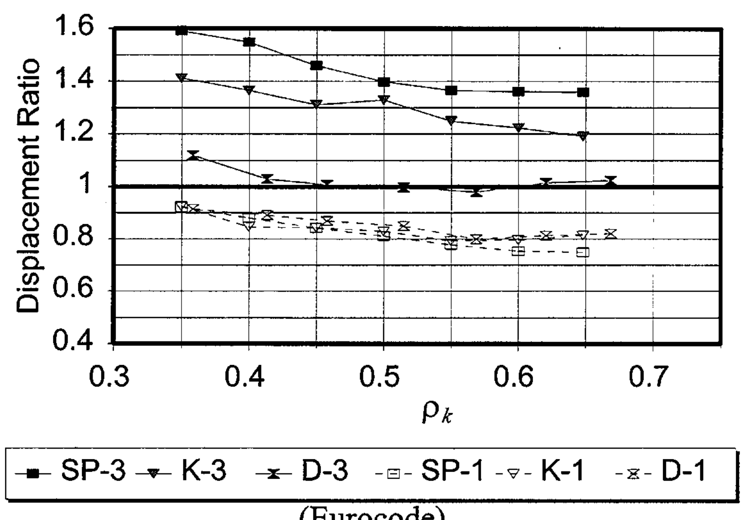

Figure 10. Mean displacement ratios of elements 1 and 3

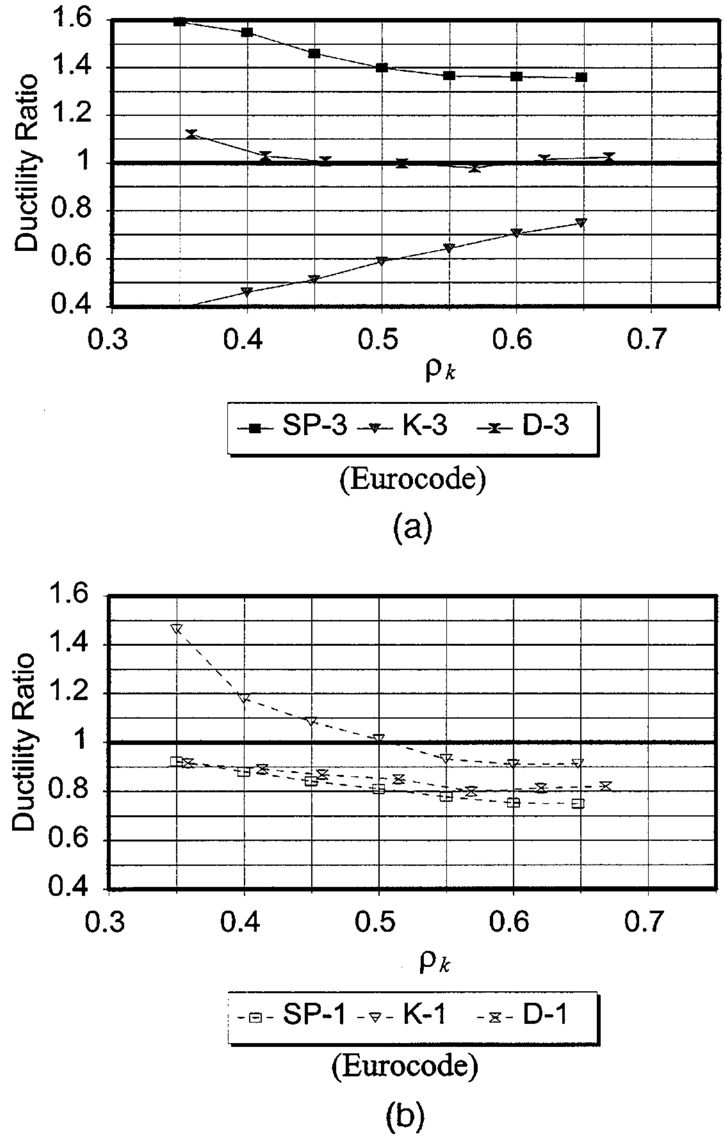

Figure 11. Mean ductility ratios of elements 1 and 3: (a) element 3, (b) element 1

Mass eccentric systems

To supplement the study of stiffness eccentric systems, the effect of applying torsional provisions to mass eccentric systems is presented in this section. The stiffness of these TU systems is symmetrically distributed resulting in CR coinciding with the geometric centre of the slab. The asymmetry of the system is caused by the uneven mass distribution of the slab, resulting in CM being located at 0·2*b* to the right of the geometric centre.

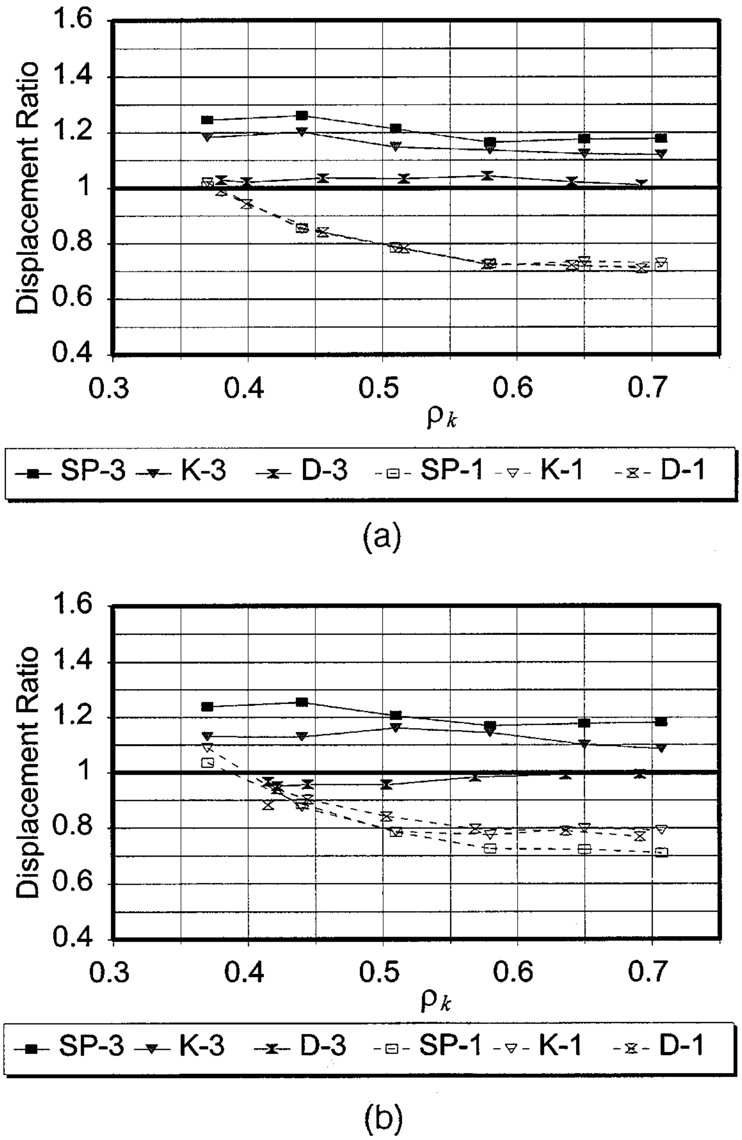

Figure 12. Mean displacement ratios for mass eccentric systems: (a) UBC-97 provision, (b) Eurocode-8 provision

The mean displacement ratios of the edge elements, using both the UBC and the Eurocode provisions, are presented in Figure 12. The additional displacement at the flexible edge for the mass eccentric systems is not as severe as the stiffness eccentric systems, even if no torsional provision is used, as shown in the SP-3 curve. The additional displacement is of the order of 20–30 per cent. The reason being that the distance from CR to element 3 is shorter for the mass eccentric systems. Application of the torsional provisions reduces the additional displacement at this edge marginally for *K*-type element systems. The control over edge displacement is much

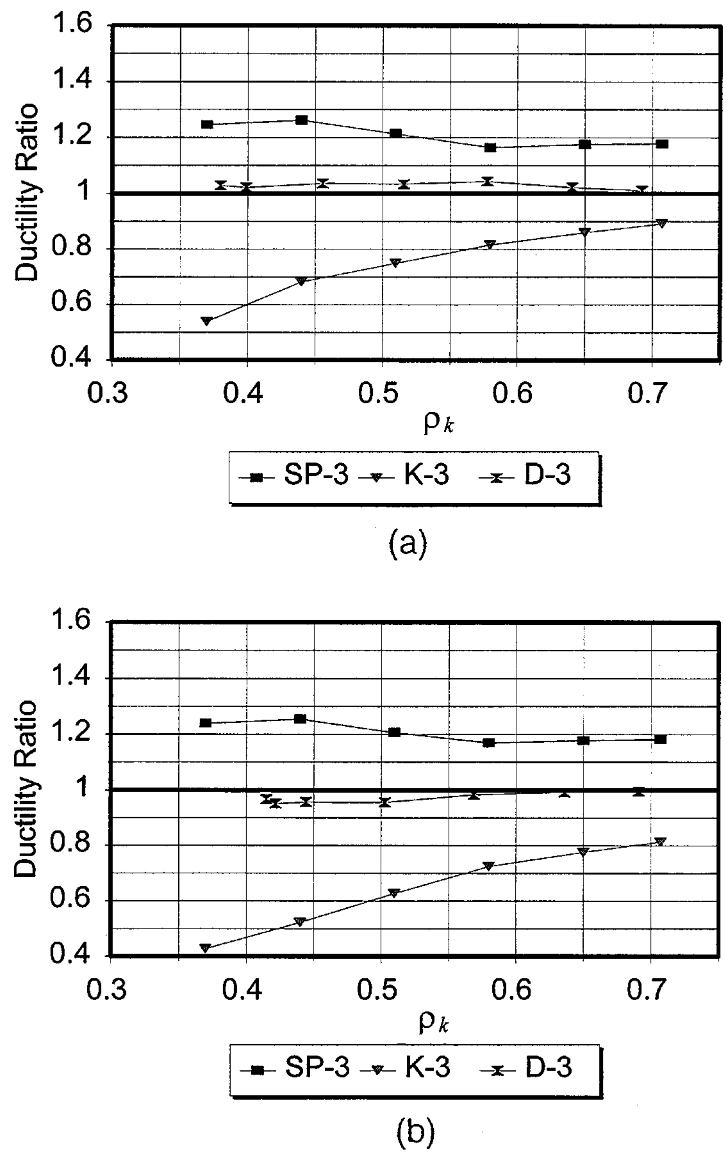

Figure 13. Mean ductility ratios for element 3 in mass eccentric systems: (a) UBC-97 provsion; (b) Eurocode-8 provision

better for D-type element systems. Application of the torsional provisions leads to essentially no additional displacement at the flexible edge. Again, the displacement ratio of element 1 at the stiff edge is insensitive to the methods of strength distribution. The displacement ratio curves for element 1 are all below unity.

The mean ductility demand ratios for element 3 are presented in Figure 13. Application of either code provision will lead to little or no additional ductility demand on this element at the flexible edge, irrespective of whether the systems have K- or D-type elements. Of more interest are

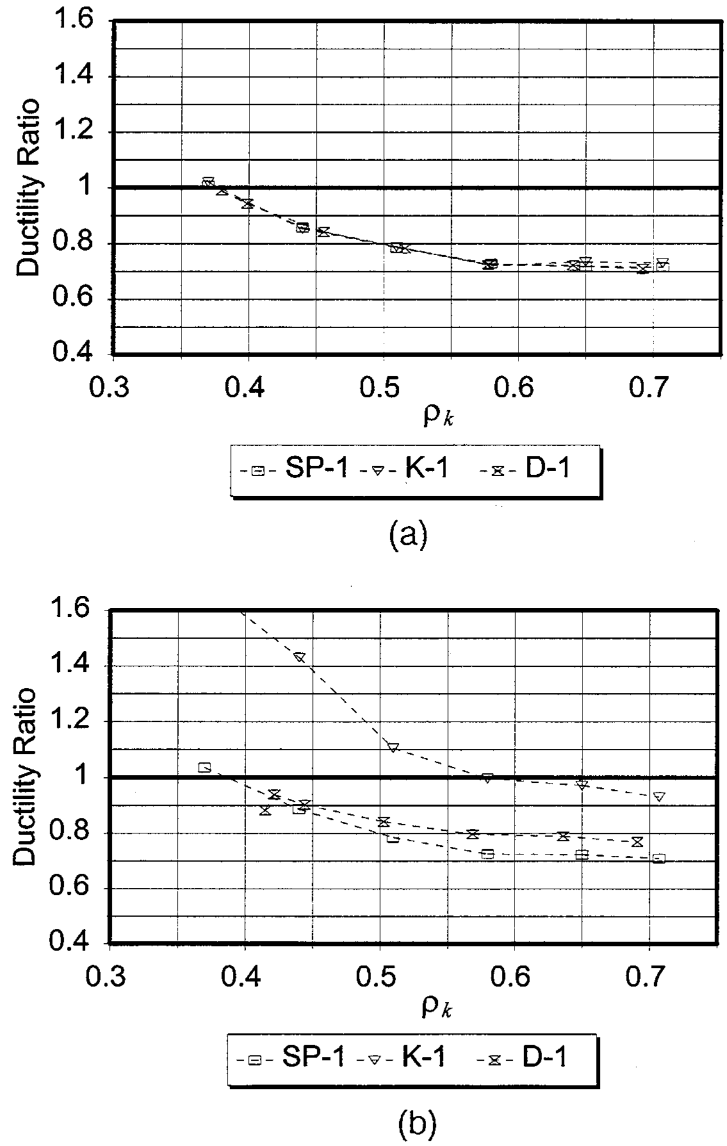

Figure 14. Mean ductility ratios for element 1 in mass eccentric systems: (a) UBC-97 provision; (b) Eurocode-8 provision

the ductility ratios for element 1 at the stiff edge. Using the UBC provision will again lead to no additional ductility demand as shown in Figure 14(a). However, application of the Eurocode provision to torsionally flexible K-type element systems can lead to substantial ductility demand increase for the element at the stiff edge, as presented in Figure 14(b). The additional ductility demand is even more severe than for stiffness eccentric systems shown in Figure 11(b).

CONCLUSIONS

Using a family of single-mass eccentric systems supported by two types of lateral load resisting elements having different characteristics, the torsional provisions of the UBC and the Eurocode were evaluated. Although the study was based on systems with moderate levels of stiffness eccentricity, and the computation was carried out using one single structural period, it is believed that the trends observed are applicable to a wider class of structural systems with different levels of eccentricity and with medium to long structural periods.

The following conclusions are drawn:

1. By simplifying structural characteristics into the *K*- and *D*-type elements, one can focus on the mechanics of strength distribution adjustment among elements and its relation to mitigate the torsional effects. For *K*-type systems, the application of torsional provisions implies changing the yield displacements of the individual elements, but does not change the stiffness eccentricity of the system. Therefore, its influence to the overall response of the system is marginal, as exemplified by the insensitivity of the edge displacements to torsional provision applications. The improvement to control additional ductility demand is the result of changing the yield displacements of the individual elements. For *D*-type systems, the application of torsional provisions changes the eccentricity of the system, but does not change the yield displacement of the elements. Therefore, its main role is to reduce the torsional response of the overall system which in turn limits additional element ductility demands.

2. It is always desirable to increase the design strength of the flexible side elements. This will increase the yield displacement of the element in a *K*-type structure, and will decrease the system eccentricity in a *D*-type structure. Either way, this would reduce the responses at the flexible side of the system. Such a step is advocated in both the UBC and the Eurocode torsional provisions.

3. The benefit of allowing the negative shear from torsion to reduce the strength of elements at the stiff edge of the eccentric system is not so apparent. It will reduce the eccentricity of the *D*-type system, and hence reduce its torsional responses. However, such practice would lower the yield displacement of the elements in a *K*-type system, thereby subjecting them to higher ductility demands. The two provisions considered differ on such a practice. The UBC provision does not allow negative shear to be taken into account in design while the Eurocode permits negative shear to reduce the strength of the stiff edge elements.

4. Application of the UBC torsional provision will prevent additional ductility demand of elements at the stiff edge, but can lead to a 10–20 per cent increase in ductility demand for elements at the flexible edge. There is no additional displacement at the stiff edge but there will be some displacement increases at the flexible edge. The worst scenario displacement increase is of the order of 30–40%. for structures with *K*-type elements, and 10–20 per cent for structures with *D*-type elements.

5. Allowing negative shear in the element strength design, the Eurocode provision provides better overall torsional response control than the UBC provision. The main drawback of the Eurocode is the possibility of having very large increases in ductility demand for *K*-type elements at the stiff edge because too much reduction in element strength is allowed. Some restriction on the amount of reduction allowed for *K*-type elements would overcome this drawback. An example of partial allowance of negative shear in the design of elements at the stiff edge can be found in the torsional provision in the National Building Code of Canada (NBCC-95).[18] Similar calculations using the NBCC torsional provision show results that are similar to those using the

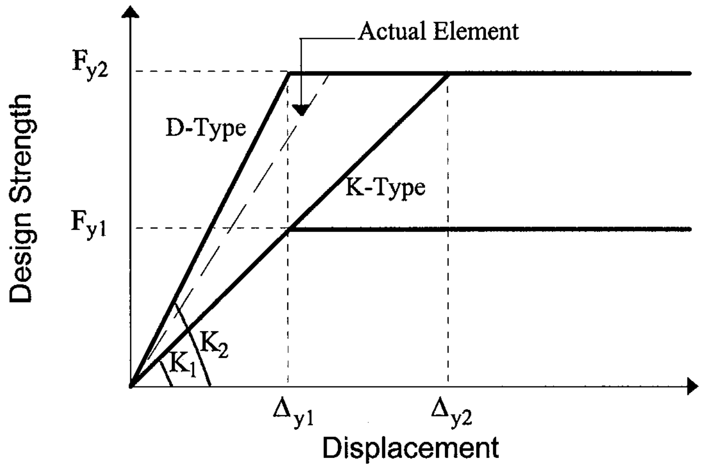

Figure 15. Typical behaviour of lateral load resisting elements

UBC provision, and the displacement and ductility demands of *D*-type elements at the flexible edge are further reduced.

6. The *K*- and *D*-type elements represent the two extreme lateral load resisting element characteristics. It is likely that in most structural elements, an increase of strength will result in some increase of both the yield displacement and the stiffness of the element. The increase in yield displacement is less than in a *K*-type element, and the increase in stiffness is less than in a *D*-type element as illustrated in Figure 15. Therefore, the results obtained assuming the lateral resisting elements are either the *K*- or *D*-type elements will envelope the likely benefit of applying two codified torsional provisions to plan-eccentric structures. Codified torsional provisions are meant to serve structures supported by elements having widely different characteristics. While the Eurocode provision works particularly well for structures with *D*-type elements, the UBC provision provides a good balance in controlling the torsional effects for structures having elements with characteristics bounded by both the *K*- and *D*-type elements. Therefore, the UBC torsional provision is a more balanced compromise for general code application.

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